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DYNAMIC DIFFUSION PROCESSES IN THE EXOSPHERE

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Introduction:

The ion-ion diffusion processes which take place in the upper
F-region can affect the distribution of both ionized and neutral
particles in the entire magnetosphere. This paper discusses several
different phenomena which may be constained in some way by these
diffusion effects.

It is to be expected, for example, that the whistler medium
will act as a giant hydrogen capacitor which stores hydrogen in the
daytime as protons, and releases them at night as atomic hydrogen.
Calculations show that this effect is probably too small to be of
importance in affecting the diurnal distribution of atomic hydrogen.
Similarly, it appears unlikely that the ionization transport between
hemispheres through the magnetosphere can greatly influence the
electron concentrations near the F_2-peak. A suggestion is made that
the energy sensitive coulomb diffusion process may affect the
exospheric ion concentrations by a "greenhouse" mechanism.

The Coulomb Diffusion Process

The process of ion-ion diffusion in the upper F-region has
been discussed by Hanson and Ortenburger[1], who showed semi-quanti-
tatively that the oxygen ions in the upper F-region present a rather

severe barrier to the flux of protons into and out of the protonosphere. The problem has since been considered in more detail by Hanson and Patterson[2], who obtained machine solutions to the appropriate diffusion equations for several sets of boundary conditions. Only the binary ion case was studied; thus the effect of helium ions on the proton-oxygen ion diffusion, for example, was neglected. It is not obvious to what extent this simplification may limit the validity of these results.

The equations for the binary-ion case are

$$\frac{\partial n_1}{\partial z} = - [\phi_1 n_2 / D(n_1 + n_2)] - n_1 [\frac{m_1 g}{kT} - \frac{eE}{kT}] \qquad (1)$$

$$\frac{\partial n_2}{\partial z} = -[(nm_1 + n_2 m_2) g/kT] + [(n_1 + n_2) eE/kT] - \frac{\partial n_1}{\partial z} \qquad (2)$$

$$\frac{\partial \phi_1}{\partial z} = S_1 - L_1 \qquad (3)$$

where n_1, n_2 and m_1, m_2 are the concentrations and masses of the two kinds of ions, g is the acceleration of gravity, k is the Boltzmann constant, T is the isothermal temperature, ϕ_1 is the upward flux of the first component, e is the electronic charge, and E is the vertical electric field. It has been assumed in the derivation of these equations that $\phi_2 = 0$, and that the kinetic energy of the diffusive transport is small compared to thermal energy. S_1 and L_1 refer to the source and loss rates per unit volume of the first constituent. The mutual diffusion coefficient D was obtained from the standard formula of Chapman and Cowling[3]:

$$D(H^+, O^+) = 8.4 \times 10^{15} \left(\frac{T}{1500}\right)^{5/2} / (n_1 + n_2) \tag{4a}$$

and

$$D(He^+, O^+) = 4.5 \times 10^{15} \left(\frac{T}{1500}\right)^{5/2} / (n_1 + n_2) \tag{4b}$$

In contrast to the ambipolar diffusion coefficient D_a which is proportional to the average of the electron and ion temperatures, D depends only on T_i. If $T_e \neq T_i$, equations (1), (2), and (3) can be corrected to first order by replacing T where it appears explicitly by the expression $(T_e + T_i)/2$.

When no external applied electric fields are present (the only case we will consider) the electric field is caused by a space charge separation in the plasma and is represented rather closely by

$$E = \frac{(n_1 m_1 + n_2 m_2)}{n_1 + n_2} \frac{g}{2e}$$

in the region well above the F_2 peak.

The only two cases considered are for hydrogen and oxygen ions, and for helium and oxygen ions. n_2 refers to oxygen ions in either case, and ϕ_2 was taken to be zero because any transient phenomena which occur will tend to approach equilibrium faster for oxygen ions because of their smaller scale height. Perhaps a more reasonable assumption would be to let $\phi_1 + \phi_2 = \phi_o$, where ϕ_o is the limiting value of ϕ_1 at high altitudes. Detailed calculations for this case, however, are not yet available. The adoption of this boundary condition is not likely to produce results which differ greatly from those presented here.

Hydrogen Transport

Whistler measurements indicate that quiet day diurnal changes of the order of 20 percent may exist in the whistler dispersion values along middle latitude magnetic field lines[4]. Even after allowances have been made for the effects of the diurnal changes in the F-region, a substantial variation ($\sim$ 30 percent) in the protonosphere concentrations can still be inferred. Because of day-night asymmetries in the magnetosphere the interpretation of these measurements is somewhat obscure, particularly at high latitudes. The total electron content[1] in a magnetic tube which has a 1 cm^2 base at 1000 km is of the order of 10^{13} electron/cm^2, a 30 percent diurnal change in this quantity would imply that a proton flux of the order of 10^8 ions $cm^{-2}sec^{-1}$ flows through the upper F-region, upwards during the daytime and downwards at night. The hydrogen ions are created during the daytime by the reaction

$$H + O^+ \rightarrow O + H^+ \tag{5}$$

and destroyed at night by the reverse reaction. Thus the protonosphere behaves like a huge capacitor, absorbing hydrogen from the atmosphere during the daytime and supplying neutral hydrogen at night. According to Kockarts and Nicolet[5], the upward flux of hydrogen from the source region below 100 km is approximately 2.5 x 10^7 atoms $cm^{-2}sec^{-1}$. If the diurnal changes in the protonosphere are really as large as 30 percent, the charging and discharging fluxes would be large compared to the source flux of hydrogen. Hence the diurnal changes in the neutral

hydrogen concentrations in the exosphere would be largely determined by this capacitor effect.

Hanson and Patterson[2], on the basis of solutions to equations (1), (2), and (3) concluded that fluxes as large as 10^8 protons $cm^{-2}sec^{-1}$ would not normally be expected on the basis of diffusion alone, as will be discussed more fully in the next section. This conclusion contradicts the possibility of having large (30 percent) diurnal protonosphere variations, and implies that the capacitor effects on the hydrogen concentrations are only comparable to, or smaller than, the effects of the source below 100 km.

The effect of lateral flow due to the concentration and temperature gradients of the hydrogen just above the base of the exosphere was also considered by Hanson and Patterson[2]. They found that this lateral flow is predominant in determining the hydrogen distribution about the earth and concluded that the hydrogen concentration near the base of the exosphere is nearly independent of local time, but that it is slightly larger at night. Nearly all of the hydrogen escape takes place on the day side where the temperature is higher. Thus the nighttime hydrogen concentrations are considerably smaller than would be calculated from Kockarts and Nicolet's analysis, and the daytime values would be nearly a factor of two larger due to the flow from the dark side.

Conjugate Ionospheric Coupling

It has been suggested that the transport of ionization between conjugate points in the F-region may exert a strong influence on the behavior of the ionization at the F_2 peak[6,7]. It is true that for quiet magnetic periods and at moderate latitudes hydrostatic equilibrium will tend to be established all along a magnetic field line, i.e., from hemisphere to hemisphere. It is also true that this equilibrium can probably be established in a few hours along the greater part of the field line.

The difficulty lies in transporting enough protons through the oxygen ion diffusion barriers to appreciably affect the F_2 peak ionization levels. Typically, the diffusion flux through the F_2 peak is of the order of 5×10^8 ions $cm^{-2}sec^{-1}$. Comparison with this value can be made by examining Fig. 1, where the ion distributions have been plotted for several different proton fluxes, both positive (upward) and negative (downward). Some of the downward fluxes shown do indeed have values $> 10^8$ $cm^{-2}sec^{-1}$. This is not true for the upward fluxes, however, the largest value shown being 2.5×10^7 $cm^{-2}sec^{-1}$. If the magnetosphere is not to be depleted of protons in time, the total upward flux per day must equal the total downward flux per day. Hence, if large downward fluxes do occur, they can last for only a relatively short time.

In principle, the calculated downward proton flux can be made arbitrarily large by increasing the high altitude proton concentration. In contrast, the upward proton flux for the steady state case has a

definite upper limit. This statement is graphically demonstrated in Fig. 1-b, where curve d represents a near maximum upward flux. Curve e, which is calculated for a slightly larger flux, is not physically allowed because the proton concentration gradients necessary to support this flux cause the proton concentration to tend to zero rapidly with increasing altitude. A similar situation is shown in Fig. 1-d.

Thus, since the fluxes which can be transported between the F_2 peaks in the two hemispheres are relatively small, there can be little effect on the F_2 peak values themselves due to this phenomena, at least at moderate latitudes.

If the upper F-region conditions are different for the two hemispheres, the concentration in the connecting tube of force will strike a compromise between the conflicting boundary conditions, with the greatest departure from hydrostatic equilibrium occurring at the end where the diffusive barrier is most effective.

The model atmosphere parameters used for the calculations made to obtain the curves in Fig. 1 are shown in Table 1; hydrostatic distributions of hydrogen and oxygen were assumed to prevail above 400 km. The use of these parameters for both daytime and nighttime conditions is not entirely legitimate. The ratio of the hydrogen and oxygen concentrations in the chemical equilibrium region is not the same on the night side as it is on the day side, since the oxygen concentration depends more on the local temperature, whereas the hydrogen concentration all around the earth depends mainly on the

temperature of the sunlit hemisphere. The particle concentrations

shown in Table I were selected for daytime conditions, so that the

proton concentrations at night would be expected to be smaller in

the chemical equilibrium region than shown in Fig. 1. If the proton

concentrations at high altitudes were kept the same as in Fig. 1, the

net result would be larger downward fluxes of protons. If instead

the same criterion used by Hanson and Patterson were applied, smaller

downward fluxes would result. Clearly, meaningful calculations of

the downward fluxes must await quantitative measurements of $n(H)$ and

$n(H^+)$ both in and above the diffusive barrier.

The Proton Greenhouse Effect

It has been shown above that the oxygen ion diffusion barrier

prevents large fluxes of thermal protons from flowing between the

F-region and the protonosphere and tends to uncouple them for times

as long as a day. Since coulomb collisions are involved, the diffusion

barrier is very energy sensitive, and it can be shown that protons with

energies greater than 10 ev will penetrate it quite readily. Consideration

of other processes shows that these fast protons are usually stopped near

the base of the neutral particle exosphere by charge-exchange with

atomic oxygen atoms. Thus, if protons are heated to this energy range

at high altitudes, the ones with pitch angles in the loss cone can escape

the protonosphere and become effectively trapped in F-region. Once

thermalized they can only slowly return to the protonosphere through

the diffusion barrier. This polarized passage of protons through the diffusion barrier is somewhat similar to the common radiation green-house effect, hence the name "proton greenhouse".

A possible result of this polarized penetration of the diffusion barrier is that the concentrations of protons at high altitudes may be very much reduced below the equilibrium values calculated as an extension to the chemical equilibrium region. The recent "knee-whistler" results reported by Carpenter[8] may arise because of this process. These data have been interpreted by Carpenter as showing a marked decrease in the ionization level beyond three and one-half to four earth radii (equatorial) during magnetically active periods. Energetic particles must be prevalent in this region during the main phase of magnetic storms, if a ring-current of sufficient magnitude is to be established[9]. Many of the ambient ions may be lost from the protonosphere during the time the ring-current is energized. In fact, it is not unlikely that nearly the entire remaining proton gas along these field lines becomes heated to several kilovolts during magnetic storms[10] and becomes geomagnetically trapped, rather than hydrostatically supported.

The possibility that the magnetosphere associated with polar magnetic latitudes may be very tenuous is important to any detailed theory of the dynamical processes taking place there. The presence or absence of a highly conducting medium is crucial to many of the arguments relating to the interactions of the solar wind with the

magnetosphere.

Transient Diffusion Phenomena

In general, the scale height of ions above the F_2 peak is greater
than the scale height of the corresponding neutral particles. This
statement is true regardless of the presence of other ions, and even
if the electron temperature is greater than the ion temperature.
(Exceptions to this generality may occur, however, when large vertical
fluxes of ions are present.) Thus when the ionization in the upper
F-region increases after sunrise, it is apparent that most of the
ionization at higher levels diffuses up from lower levels and does
not arise from local photo-ionization. The effect is only partially
offset by the earlier sunrise at higher altitudes.

The distortion of the oxygen ion region just above the F_2
peak due to this upward diffusion is only slight, but the effect on
the helium ion distribution could be very dramatic, particularly if
the helium ions largely disappear at night. An example of what might
occur is shown in Figure 2. Only helium ions and oxygen ions are shown;
the presence of hydrogen ions was ignored in the calculations that
were used to determine the ion distributions shown in the figure.

The helium ion distributions were calculated by fixing their
concentration at 1100 km at some value below the equilibrium value,
and by assuming the oxygen ion distribution shown in Figure 2. The
source and loss rates due to photoionization and ion-atom interchange

respectively were represented by the functions

$$S_1 = 3 \times 10^{-8} \, n(He) \text{ ions/cm}^3 \text{ sec} \qquad (6)$$

and

$$L_1 = 5 \times 10^{-10} \, n(O_2) \, n(He^+), \qquad (7)$$

where $n(x)$ is the concentration of constituent x, and hydrostatic distributions of O_2 and He were assumed. The concentrations of O_2 and He were both taken to be $1.5 \times 10^6 \text{ cm}^{-3}$ at 350 km; the steady state solution to (1), (2), and (3) was then obtained. While it is unlikely that the helium ion concentration would decrease to such small values at night[11], the drastic modification of minor ion distributions which might possibly occur is dramatically shown by the double maximum in the He$^+$ distribution in curve (a).

The use of such a large rate constant in (7) can be justified by re-evaluating equation (10) of Hanson[11] by noting[12] that O_2 rather than N_2 is responsible for the destruction of He$^+$. The right hand side of Hanson's[11] expression (10) should further be multiplied by a factor of 8 (the ratio of the helium to molecular oxygen scale heights) to take into account the difference in the creation and destruction volumes of the helium ions. The appropriate equation for the rate constant of He$^+$ with O_2 then becomes

$$k = \frac{8 \times 3 \times 10^{-8} \, n(He)}{n(He^+) n(O_2)} \qquad (8)$$

which is to be evaluated at 380 km. The resultant value for k is

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approximately 5×10^{-10} cm^{3}sec^{-1}. This value is reasonably consistent with a value which can be derived from the analysis of Bates and Patterson[12].

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FIGURE CAPTIONS

Fig. 1. Calculated distributions of protons and oxygen-ions for various vertical fluxes of protons. The limiting value of the proton flux is shown for each curve; upward fluxes are called positive. Figs. 1-a, 1-b, 1-c, and 1-d correspond to different model atmospheres which are characterized by the parameters given in Table 1. Only downward fluxes are shown in Fig. 1-a because an exospheric temperature of 750° is considered unlikely during the daytime, when upward fluxes are most probable. For the opposite reason, only upward fluxes are shown in Fig. 1-d. It is interesting to note that the force field caused by collisions of oxygen ions with the moving proton gas can appreciably alter the oxygen ion scale height at high altitudes.
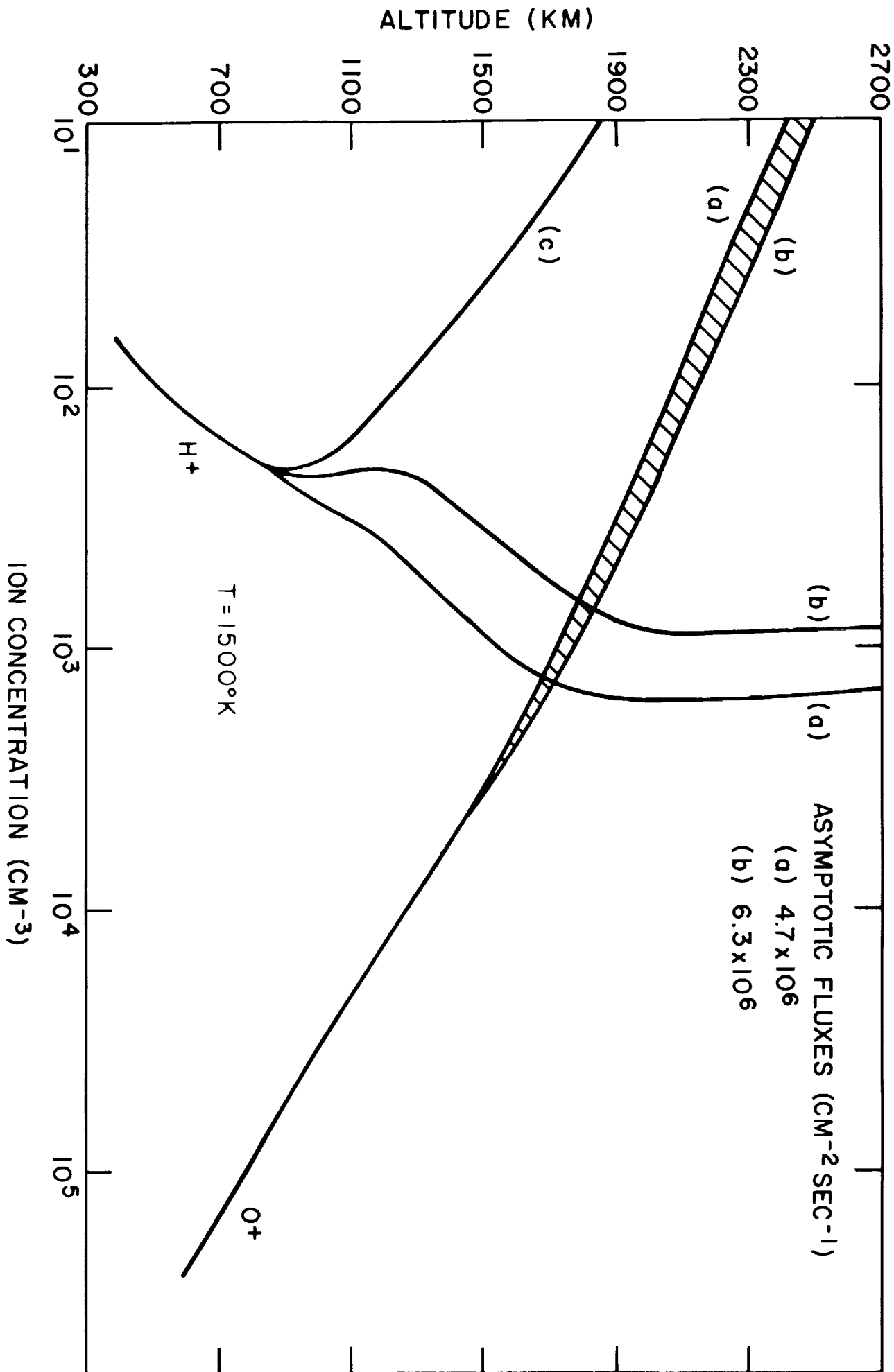
Fig. 2 Calculated distributions of helium- and oxygen-ions under sunlit conditions obtained by arbitrarily choosing small helium ion concentrations at 1100 km.
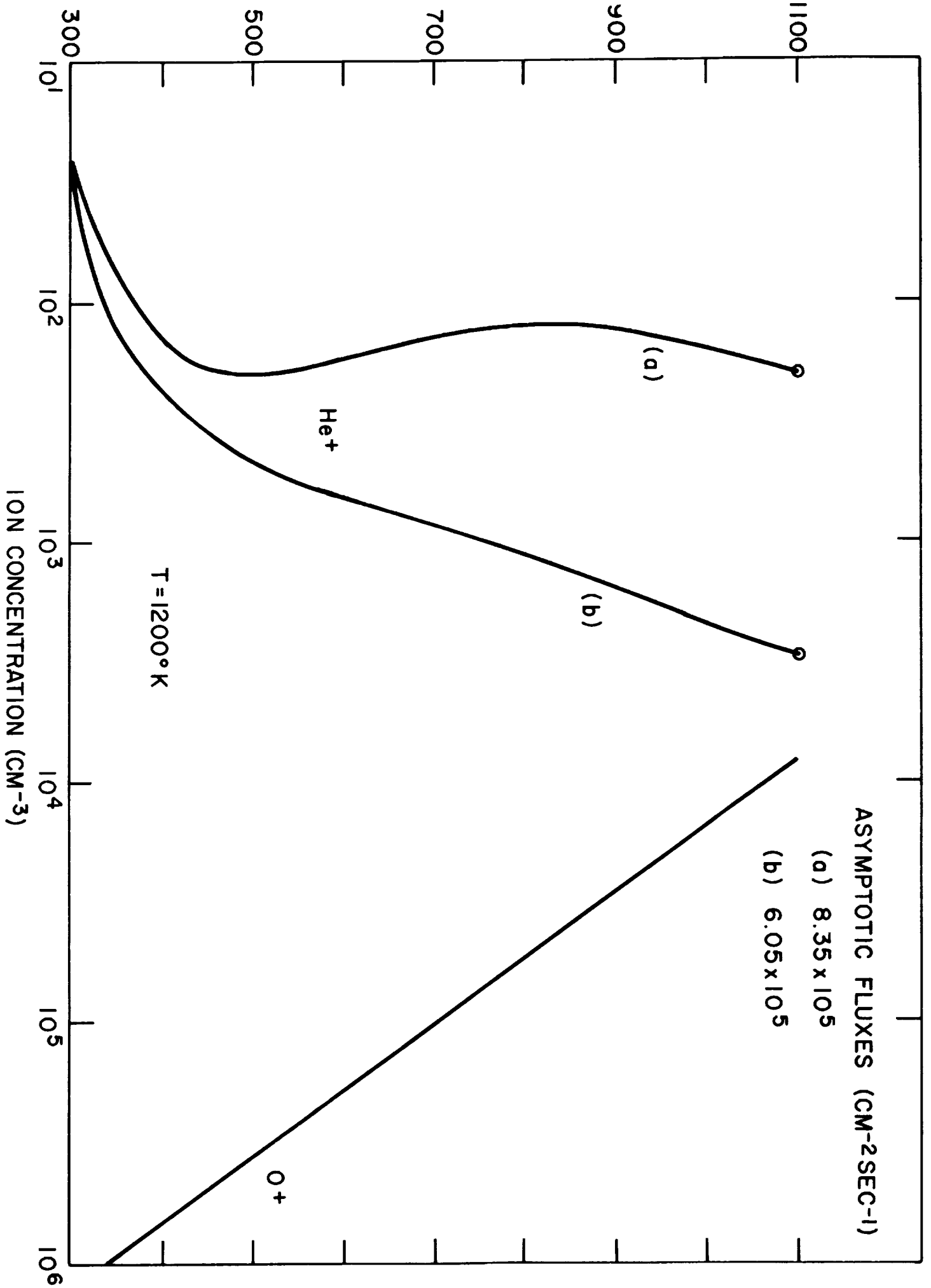
TABLE I

Model Atmosphere Parameters for Figure I

Temperature	n(O) at 400 km	n(H) at 400 km
750 °K	3.2×10^7 cm^{-3}	1.9×10^5 cm^{-3}
1000 °K	1.0×10^8 cm^{-3}	1.0×10^5 cm^{-3}
1250 °K	1.5×10^8 cm^{-3}	3.0×10^4 cm^{-3}
1500 °K	3.0×10^8 cm^{-3}	1.0×10^4 cm^{-3}

Fig. 3

Fig. 5.

Fig. 6.

Fig. 7